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ABSOLUTE AND RELATIVE MOTION MEASUREMENTS ON A MODEL OF A HIGH-SPEED CONTAINERSHIP

by

John F. O'Dea

Harry D. Jones

Presented at the
20th American Towing Tank Conference
Stevens Institute of Technology
Hoboken, New Jersey
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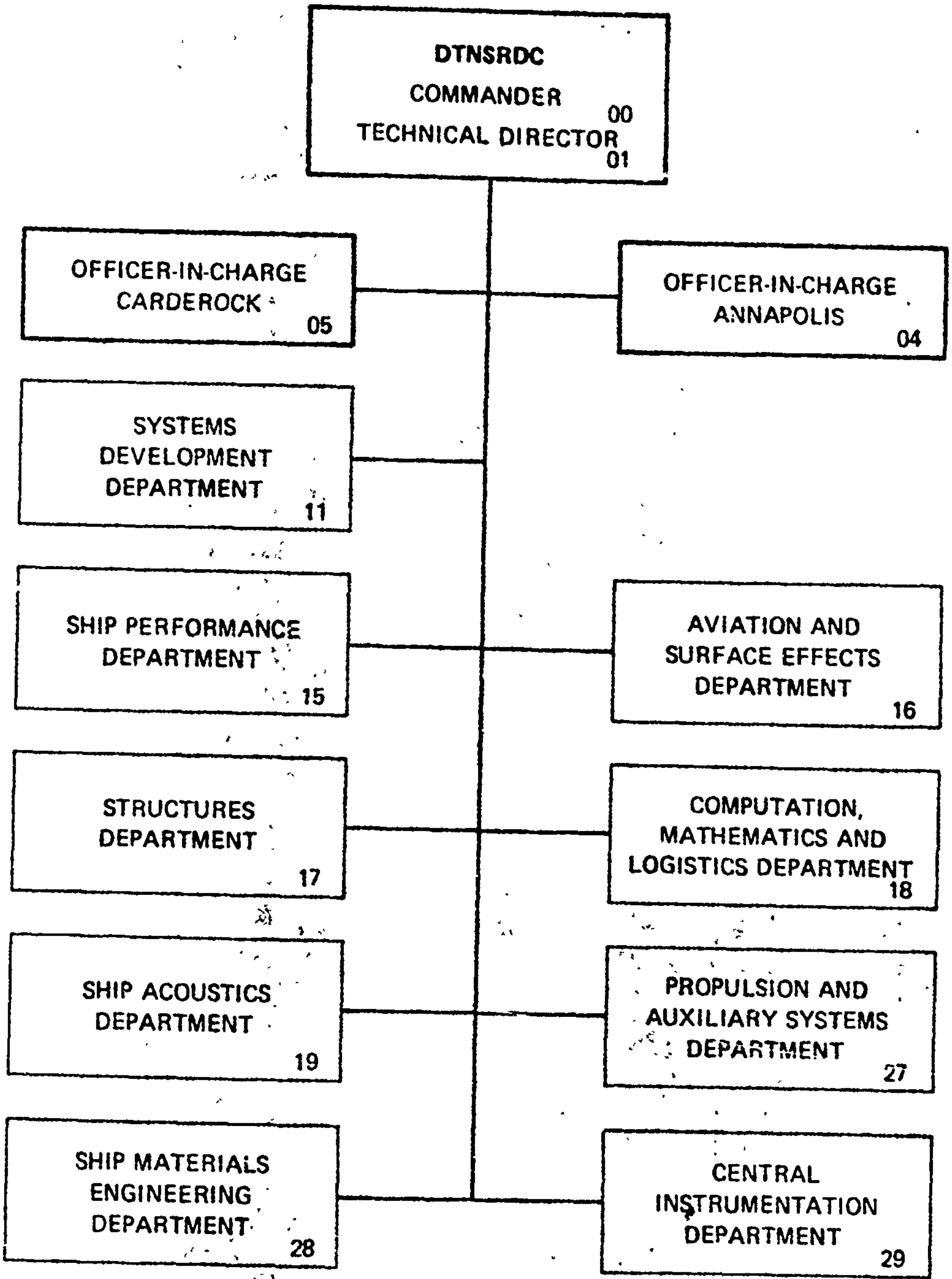

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John F. O'Dea and Harry D. Jones
David W. Taylor Naval Ship Research and Development Center

ABSTRACT

A series of experiments was performed to measure the added mass and damping coefficients, and the radiated wave component of relative motion at the bow, for a model of the SL-7 containership. The coefficients of the uncoupled motions agree well with strip theory predictions, but the cross-coupling coefficients between heave and pitch are not well predicted. When the measured values of the coefficients are used in the equations of motion, the calculated motions agree well with the measured motions of a freely floating hull. The measured radiated wave component of relative motion is consistently larger than predicted by strip theory, and has a different phase angle.

INTRODUCTION

One of the important measures of a ship's seakeeping performance is the relative vertical motion between the ship and water surface, particularly near the bow. This relative motion has a strong influence on slamming and deck wetness in a seaway. In the past, the relative motion has been calculated using a kinematic approach, taking the difference between the absolute vertical motion at a given location on the hull and the undisturbed incident wave elevation at that location. This approach was not entirely satisfactory, since interference between the ship and waves (sometimes referred to as "dynamic swell-up") was not taken into account. Recently, several attempts have been made to improve calculations

of relative motion by calculating the hull diffraction effect on the incident waves and the waves generated by the oscillation of the hull (Beck,[1] Lee et al.[2]).

While there is no question that these effects must be included if improvements are to be made in the prediction of relative motion, it must also be recognized that accurate prediction of the rigid body motions is a prerequisite to calculation of relative motion. Both amplitude and phase of the heave and pitch transfer functions affect the calculation of absolute vertical motion in head seas, and if the absolute vertical motion near the bow is not accurately calculated the relative motion calculation will be in error.

It is commonly assumed that the strip theory presented by Salvesen, Tuck and Faltinsen[3] (STF) can be used with confidence to predict longitudinal motions of conventional, monohull displacement ships at moderate Froude number. However, this may not always be true. It has been found in previous experimental work with the SL-7 hull that, at moderately high speed (Froude number = 0.30) in head seas, the magnitude of heave was poorly predicted. There are also motion prediction methods, such as the rational strip theory of Ogilvie and Tuck,[4] and the unified slender body theory of Newman and Sclavounos,[5] which in some cases predict added mass and damping coefficients which are noticeably different from those calculated using the ordinary strip theory of Salvesen.

The discrepancy between prediction and measurement of the rigid body motions motivated a series of forced oscillation experiments on the SL-7

hull, designed to measure the various components of the rigid body equations of motion and determine the source of the discrepancy. At the same time, the relative motion in the region of the bow was measured so that the hull generated component of relative motion could be compared to strip theory predictions. The results of these oscillation experiments are presented in this paper.

EQUATIONS OF MOTION

The coupled equations of motion of a heaving and pitching ship may be written as:

$$\begin{aligned}(M + A_{ZZ})\ddot{Z} + B_{ZZ}\dot{Z} + C_{ZZ}Z + A_{Z\theta}\ddot{\theta} + B_{Z\theta}\dot{\theta} + C_{Z\theta}\theta &= F_Z \\ A_{\theta Z}\ddot{Z} + B_{\theta Z}\dot{Z} + C_{\theta Z}Z + (Mk_y^2 + A_{\theta\theta})\ddot{\theta} + B_{\theta\theta}\dot{\theta} + C_{\theta\theta}\theta &= M_\theta\end{aligned} \qquad (1)$$

where k_y is the radius of gyration in pitch, A, B, and C refer to the added mass, damping and hydrostatic coefficients, Z and θ are the heave and pitch motions, and F_Z and M_θ denote the heave exciting force and pitch exciting moment respectively. For steady sinusoidal motion the motion and excitation terms can be expressed as complex amplitudes containing both magnitude and phase information:

$$Z = \mathrm{Re}[Z_o e^{i\omega t}],\ \dot{Z} = \mathrm{Re}[i\omega Z_o e^{i\omega t}],\ \text{etc.}$$

It is also convenient to represent all the terms in the equations of motion in nondimensional from, as shown in Table 1. The equations of motion may then be written as a set of algebraic equations with complex coefficients:

$$\begin{aligned}[C'_{ZZ} - \sigma^2(1+A'_{ZZ}) + i\sigma B'_{ZZ}]Z'_o + [C'_{Z\theta} - \sigma^2 A'_{Z\theta} + i\sigma B'_{Z\theta}]\theta'_o &= F'_Z \\ [C'_{\theta Z} - \sigma^2 A'_{\theta Z} + i\sigma B'_{\theta Z}]Z'_o + [C'_{\theta\theta} - \sigma^2(k'^2_y + A'_{\theta\theta}) + i\sigma B'_{\theta\theta}]\theta'_o &= M'_\theta\end{aligned} \qquad (2)$$

For the purpose of determining the added mass and damping coefficients, the hull can be oscillated with a single degree of freedom at a time. The resultant force and moment on the hull may then be used to determine the coefficients. The hydrostatic coefficients may be calculated from the waterplane characteristics or measured by static displacement of the hull.

For example, for forced heave oscillation, let the heave motion Z be defined as a real quantity, so that it is the zero phase reference, and let the force and moment in this case be made nondimensional by heave amplitude rather than incident wave amplitude. The equations of motion then become:

$$\begin{aligned} C'_{ZZ} - \sigma^2(1 + A'_{ZZ}) + i\sigma B'_{ZZ} &= F'_Z \\ C'_{\theta Z} - \sigma^2 A'_{\theta Z} + i\sigma B'_{\theta Z} &= M'_\theta \end{aligned} \tag{3}$$

and the added mass and damping terms associated with heave motion are found as:

$$\begin{aligned} A'_{ZZ} &= \frac{C'_{ZZ} - \mathrm{Re}[F'_Z]}{\sigma^2} - 1 \\ B'_{ZZ} &= \frac{\mathrm{Im}[F'_Z]}{\sigma} \\ A'_{\theta Z} &= \frac{C'_{\theta Z} - \mathrm{Re}[M'_\theta]}{\sigma^2} \\ B'_{\theta Z} &= \frac{\mathrm{Im}[M'_\theta]}{\sigma} \end{aligned} \tag{4}$$

In a similar way, if a pure pitch motion (about the center of gravity) is applied to the hull, and the resulting force and moment F_Z, M_θ are made nondimensional as:

$$F_Z^* = \frac{F_Z}{\rho g \nabla \theta}, \quad M_\theta^* = \frac{M_\theta}{\rho g \nabla L \theta}$$

then the added mass and damping terms are found to be:

$$\begin{aligned}
A'_{Z\theta} &= \frac{C'_{Z\theta} - \mathrm{Re}[F_Z^*]}{\sigma^2} \\
B'_{Z\theta} &= \frac{\mathrm{Im}[F_Z^*]}{\sigma} \\
A'_{\theta\theta} &= \frac{C'_{\theta\theta} - \mathrm{Re}[M_\theta^*]}{\sigma^2} - k_y'^2 \\
B'_{\theta\theta} &= \frac{\mathrm{Im}[M_\theta^*]}{\sigma}
\end{aligned} \tag{5}$$

EXPERIMENTAL SETUP AND INSTRUMENTATION

The forced oscillation experiments were performed using a 1:60 scale model of the SL-7 containership ballasted to a 0.173m waterline with a pitch radius of gyration equal to 0.254 times the length between perpendiculars. The coordinate origin of the axis system used in the experiments was taken at the center of gravity of the hull, with heave motion and force defined as vertically upward and pitch motion and moment defined as bow down. The oscillator used was a single degree-of-freedom Scotch yoke type with maximum stroke of ± 1 inch (25.4 mm) and a variable frequency controlled by a servo system on the DC driving motor. In the heave experiment the model

was connected to the oscillator through four load cells and a rigid frame (the load cells were mounted port and starboard, at approximately $\pm L/4$ with pivot joints to avoid out-of-axis loads). For the pitch oscillation experiment the aft pair of load cells was moved to the hull center of gravity and attached to the carriage through pivots, while the oscillator was used to vertically oscillate the forward attachment point.

Using the full range of the oscillator, it was possible to achieve a heave magnitude equal to approximately 15% of the draft of the hull. It was also decided that a maximum nondimensional frequency ($\omega\sqrt{L/g}$) equal to 10 was desirable. This frequency corresponded to a wavelength ratio, $\lambda/L < 0.5$ at a Froude number of 0.3. Using these values, and estimates of added mass from strip theory, the maximum heave oscillation force was estimated to be approximately 1000 N, and the load cells were calibrated accordingly. Using the same load cell range in the pitch oscillation experiment the maximum pitch amplitude was limited to approximately ± 0.6 degrees. Since the intention was to check the linear coefficients of the equations of motion, these oscillation amplitudes were considered adequate.

Relative motion was measured at stations 0,1,2 and 3 using resistance-type probes mounted flush to the side of the hull. Time histories of force, oscillation amplitude, carriage speed and relative motion were digitized by an on-board DEC 11/23 computer and recorded on magnetic disk. The records were harmonically analyzed and resolved into inertia and damping coefficients according to Equations (4) and (5).

RESULTS

The results of the oscillation experiments are shown in Figures 1 to 8. In each case, the experiments, were done at three speeds corresponding to Froude number = 0.1,0.2 and 0.3, and nondimensional frequency varied from approximately 2.0 to 8.5. The heave experiments were done over the full range of frequencies at an amplitude $Z_o/T = 0.037$, and repeated with amplitudes up to $Z_o/T = 0.147$ at selected frequencies. The pitch experiments were done over the full frequency range at an amplitude of 0.37 degrees, and repeated for selected frequencies at 0.19 and 0.56 degrees.

The uncoupled coefficients A_{ZZ}, B_{ZZ}, $A_{\theta\theta}$ and $B_{\theta\theta}$, shown in Figures 1 to 4 are generally in very good agreement with predictions made by strip theory. This is particularly true in the range $3<\sigma<5$, corresponding to a range of wavelengths near the ship length where motion predictions are most crucial. The only area where significant scatter is shown in the data is in the low speed results near $\sigma \leq 2.5$, corresponding to $\omega \frac{U}{g} = 1/4$ where free surface waves can be radiated ahead of the hull. This introduces the possibility of reflected waves reaching the hull, resulting in the poor data shown. The corresponding condition at the higher Froude numbers would occur outside the frequency range tested; therefore no such scatter appears in the data at these speeds.

Results for the cross coupling coefficients $A_{\theta Z}$, $B_{\theta Z}$, $A_{Z\theta}$ and $B_{Z\theta}$ are shown in Figures 5 to 8. There are significant discrepancies between predicted and measured values for all these coefficients. The predicted and measured coefficients converge at the highest frequencies but diverge

over much of the frequency range, particularly the range where cross coupling has a strong effect on the motions as discussed below. These discrepancies are qualitatively similar to those reported by Faltinsen,[6] who found a significant improvement when the extra components of the Ogilvie-Tuck theory were added to the ordinary (STF) strip theory.

Experimental values of heave and pitch excitation were available from an earlier, unpublished experiment on this hull. These data were obtained with the model rigidly attached to the towing carriage, with incident waves of steepness $2\zeta_A/\lambda=1/50$. The results of these experiments are shown in Figures 9 to 12. In general, the heave excitation magnitude agrees well with strip theory predictions, as does the heave excitation phase angle except at high frequencies, corresponding to wave lengths shorter than the ship length where phase angles shift rapidly with changing frequency. Similar agreement is found for pitch excitation although there is an overall trend for the measured pitch excitation to be slightly less than the predicted values.

The experimentally measured added mass, damping and excitation coefficients have been used in the equations of motion to calculate the heave and pitch motions. The results are shown in Figures 13 and 14, together with strip theory predictions and experimental values on a freely floating model. The heave motion measured on the freely floating hull is considerably closer to the calculations made with the measured coefficients, than to the strip theory predictions. This is particularly true at Froude number = 0.3. The effect of using the measured coefficient in calculating pitch is less obvious, and at Froude number = 0.3 in the low frequency range, the use of

the measured coefficients actually gives slightly poorer predictions than strip theory.

The measured values of relative motion in the oscillation experiments are shown in Figures 15 to 18 for stations 0, 1, 2 and 3 respectively. These figures show the magnitude of relative motion measured by the resistance wire probes made nondimensional by the corresponding absolute vertical motion at the particular station (either heave amplitude or pitch amplitude times the lever arm to that station). Thus, even when no local wave is generated by the hull, the nondimensional relative motion has a value of 1.0. The degree to which the data in the figures deviates from a value of 1.0, therefore, is an indication of the importance of the hull-generated wave component in relative motion.

Relative motion data are shown in each figure for the four amplitudes of heave motion used in the oscillator experiments and for one pitch amplitude. There is a trend for the results at the smallest heave amplitude to be slightly larger than at the larger amplitudes. This was possibly caused by surface tension effects at the smallest amplitude or by a small bias in setting the oscillation amplitude. All the other results show no particular trend with oscillation amplitude. The results for the pitch oscillation are generally close to the results for heave oscillation, when both are nondimensionalized by the local absolute vertical motion.

The results for stations 0 and 1 show little effect from hull generated waves. This is not surprising, since the hull cross-section at these stations is very small. At station 2, the magnitude of the relative motion reaches

approximately 1.25, and at station 3 at high frequencies it reaches a value of 1.5, indicating a significant hull generated wave component. Although not shown, the phase of the relative motion, referenced to the phase of the local absolute motion, was very close to 180 degrees at stations 0 and 1, since in the absence of a local wave effect the relative motion reaches a maximum positive value at the point where the hull reaches its deepest immersion (maximum negative absolute vertical motion). The phase of the relative motion at station 2 indicated a further phase lead of 5 to 10 degrees and at station 3 a lead of 15 to 20 degrees, compared to the phase at stations 0 and 1. This indicates that the hull generated wave at stations 2 and 3 was not exactly in phase with the motion.

The hull generated wave component of relative motion, as predicted by strip theory, is shown in Figure 19 for station 2 at Froude number = 0.3. As shown, the phase angle of this component lags the absolute motion by approximately 90 degrees. Since the relative motion is the vector difference between the absolute motion and hull generated wave, and the latter is typically a fraction of the former, the relative motion predicted by strip theory would show very little influence from the hull generated wave if it is phase shifted 90 degrees from the absolute motion. In contrast, when the measured value of relative motion reaches a magnitude of approximately 1.25 at this station, it is an indication that the hull generated wave has a magnitude of at least 0.25, and the phase of this wave component is closer to 180 degrees than to 90 degrees.

EXPERIMENTAL ACCURACY

The accuracy of oscillation experiments can be affected by many factors. The first is the accuracy of the oscillation motion itself. If the oscillator motion is not purely sinusoidal, or if there is vibration of the carriage, the measured forces and moments will be distorted. While harmonic analysis of the time histories will filter most of the unwanted portion, the effective signal-to-noise ratio will be reduced. It was found in the experiments reported here that there was a background noise level in all of the force gages of approximately one Newton RMS. This was presumably caused by carriage vibration, and did not vary with carriage speed. The oscillator motion itself was very nearly a pure sinusoid, with the first harmonic typically accounting for about 99% of the total mean square energy of the motion signal. The magnitude of the force signals was typically much large than the background noise level, except for the smallest oscillator amplitudes and lowest oscillation frequencies. However, even in these cases the first harmonic of the force signals typically were greater than 50% of the total energy.

Another factor in the accuracy of the experiments is the degree to which the hydrostatic coefficients, measured from static displacement of the hull, agree with calculations using the waterplane characteristics of the hull. It was found that the heave static coefficients, as measured by the slope of static force and moment against static heave displacement, agreed very well with calculated values. Of course, there was an offset of the

intercept of such calibration curves which increased with Froude number, This is reccgnized as the steady forward speed loads causing sinkage and trim on a freely floating hull and in fact the measured offset values correlated well with measured sinkage and trim values previousy measured on this hull. In the pitch oscillation experiments, there was a noticeable discrepancy between the measured and calculated pitch hydrostatic coefficient, $C_{\theta\theta}$. This was apparently caused by some residual stiffness in the hardware which was accentuated by the very small oscillation amplitudes used. There was also a small apparent tendency for this static coefficient to vary with forward speed. The experimentally measured values of all the static coefficients were used in analyzing the results according to Equations (4) and (5), but the uncertainty concerning $C_{\theta\theta}$ makes the values of $A_{\theta\theta}$ perhaps the least reliable of all the dynamic coefficients.

The accuracy of the relative motion probes on the bow is a function of their linearity, sensitivity, and possible surface tension effects. These probes were originally designed to measure relative motion over a large range, from bottom emersion to deck immersion. However, their electronic sensitivity was adjusted for these experiments in recognition of the fact that oscillation amplitudes would only be a fraction of the draft, and in fact the small amplitudes served to reduce possible nonlinearities, since the hull was effectively wall-sided in the oscillation range. However, the small oscillation amplitudes may have introduced surface tension effects, since the probes were in physical contact with the water surface, and the size of the meniscus was not necessarily negligible in comparison to measured magnitudes.

In considering the accuracy of the various coefficients, one must consider the magnitude of the force or moment component associated with a particular coefficient, in relation to the vector sum of all the forces or moments in the equations of motion. The relative balance between the components is a function of frequency. That is, at low frequencies the equations are dominated by hydrostatic effects, while at very high frequencies inertial effects predominate. This means that the accuracy of measuring added mass will be good at high frequencies, but at low frequencies one may expect rather more scatter in the added mass data since the inertial part is only a small fraction of the real part (or in-phase component) of the force or moment. If there is an error in the corresponding hydrostatic coefficient, a bias will be introduced into the low-frequency added mass estimates, in addition to increased scatter.

In an intermediate frequency range, the static and inertial terms tend to cancel each other, with the phase of the net force or moment approaching a 90 degree shift from the motion itself. This corresponds to the resonance condition for a mechanical oscillator. In this situation the total force or moment is dominated by the damping term, so that the most accurate measurements of damping are expected in the intermediate frequency range. Implicit in the discussion above is the need to measure phase angles accurately, since the forces and moments for arbitrary frequencies contain information about both damping and inertial coefficients, and the real and maginary parts must be carefully separated.

A final measure of the accuracy of the experiments is the repeating of conditions which was done at different oscillation ampltitudes. This is a check both on repeatability (the degree of scatter) and linearity (trends with amplitude). In these experiments, very little nonlinearity was observed. There is some tendency for the measurements at the very smallest oscillation amplitude to differ from other amplitudes, but this may be simply an indication of the limit of the accuracy with which the actual oscillation amplitude could be set. The smallest amplitudes corresponded to only a few millimeters at the oscillator attachment point so that even a tenth of a millimeter might bias the results. Other than this, there was no discernable nonlinear trend in any of the results, and the variation between results at different amplitudes would have been considered quite acceptable scatter even if only one amplitude had been repeated.

CONCLUSIONS

The measured coefficients of heave and pitch motion of the SL-7 show good agreement with strip theory for the uncoupled coefficients. However, the cross coupling coefficients show a considerable discrepancy at all but the highest frequencies of oscillation. The measured wave excitation loads are in reasonable agreement, with measured pitch exciting moment being somewhat less than predicted by strip theory. When the measured values of added mass, damping and excitation are used in the equations of motion, the resulting calculated values of heave and pitch response show improved correlation to the measured motions on a freely floating hull, particularly at high speed.

The measured relative motion near the bow due to forced heave or pitch motion is consistently higher than predicted by strip theory. The phase angle of the measured relative motion is close to 180 degrees from the motion phase, indcating that the hull generated wave is also near this phase angle. This tends to maximize the relative motion, while the 90 degree phase shift predicted by strip theory tends to minimize the effect of the generated wave on relative motion.

ACKNOWLEDGMENT

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REFERENCES

1. Beck, Robert F., "Relative Motion Components for a Mathematical Form in Regular Waves," 14th Symposium on Naval Hydrodynamics, Ann Arbor, Michigan, August 1982.

2. Lee, Choung M., John F. O'Dea and William G. Meyers, "Prediction of Relative Motion of Ships in Waves," 14th Symposium on Naval Hydrodynamics, Ann Arbor, Michigan, August 1982.

3. Salvesen, Nils, E. O. Tuck and Odd Faltinsen, "Ship Motions and Sea Loads," Transactions SNAME, 1970.

4. Ogilvie, T.F. and E.O. Tuck, "A Rational Strip Theory of Ship Motions, Part 1," University of Michigan, Department of Naval Architecture and Marine Engineering, Report 013, 1969.

5. Newman, J. Nicholas and Paul Sclavounos, "The Unified Theory of Ship Motions," 13th Symposium on Naval Hydrodynamics, Tokyo, 1980.

6. Faltinsen, Odd M., "A Numerical Investigation of the Ogilvie-Tuck Formulas for Added-Mass and Damping Coefficients," Journal of Ship Research, June 1974.

TABLE 1 - NON-DIMENSIONAL COEFFICIENTS

$$A'_{zz} = \frac{A_{zz}}{\rho\nabla} \qquad B'_{zz} = \frac{B_{zz}}{\rho\nabla}\sqrt{L/g} \qquad C'_{zz} = \frac{C_{zz}}{\rho g \nabla/L}$$

$$A'_{z\theta} = \frac{A_{z\theta}}{\rho\nabla L} \qquad B'_{z\theta} = \frac{B_{z\theta}}{\rho\nabla L}\sqrt{L/g} \qquad C'_{z\theta} = \frac{C_{z\theta}}{\rho g \nabla}$$

$$A'_{\theta z} = \frac{A_{\theta z}}{\rho\nabla L} \qquad B'_{\theta z} = \frac{B_{\theta z}}{\rho\nabla L}\sqrt{L/g} \qquad C'_{\theta z} = \frac{C_{\theta z}}{\rho g \nabla}$$

$$A'_{\theta\theta} = \frac{A_{\theta\theta}}{\rho\nabla L^2} \qquad B'_{\theta\theta} = \frac{B_{\theta\theta}}{\rho\nabla L^2}\sqrt{L/g} \qquad C'_{\theta\theta} = \frac{C_{\theta\theta}}{\rho g \nabla L}$$

$$F'_Z = \frac{F_Z}{\rho g(\nabla/L)\,\zeta_A} \qquad M'_\theta = \frac{M_\theta}{\rho g \nabla\,\zeta_A}$$

$$Z'_o = \frac{Z_o}{\zeta_A} \qquad \Theta'_o = \frac{L\Theta_o}{\zeta_A}$$

$$k'_y = \frac{k_y}{L} \qquad \sigma = \omega\sqrt{L/g}$$

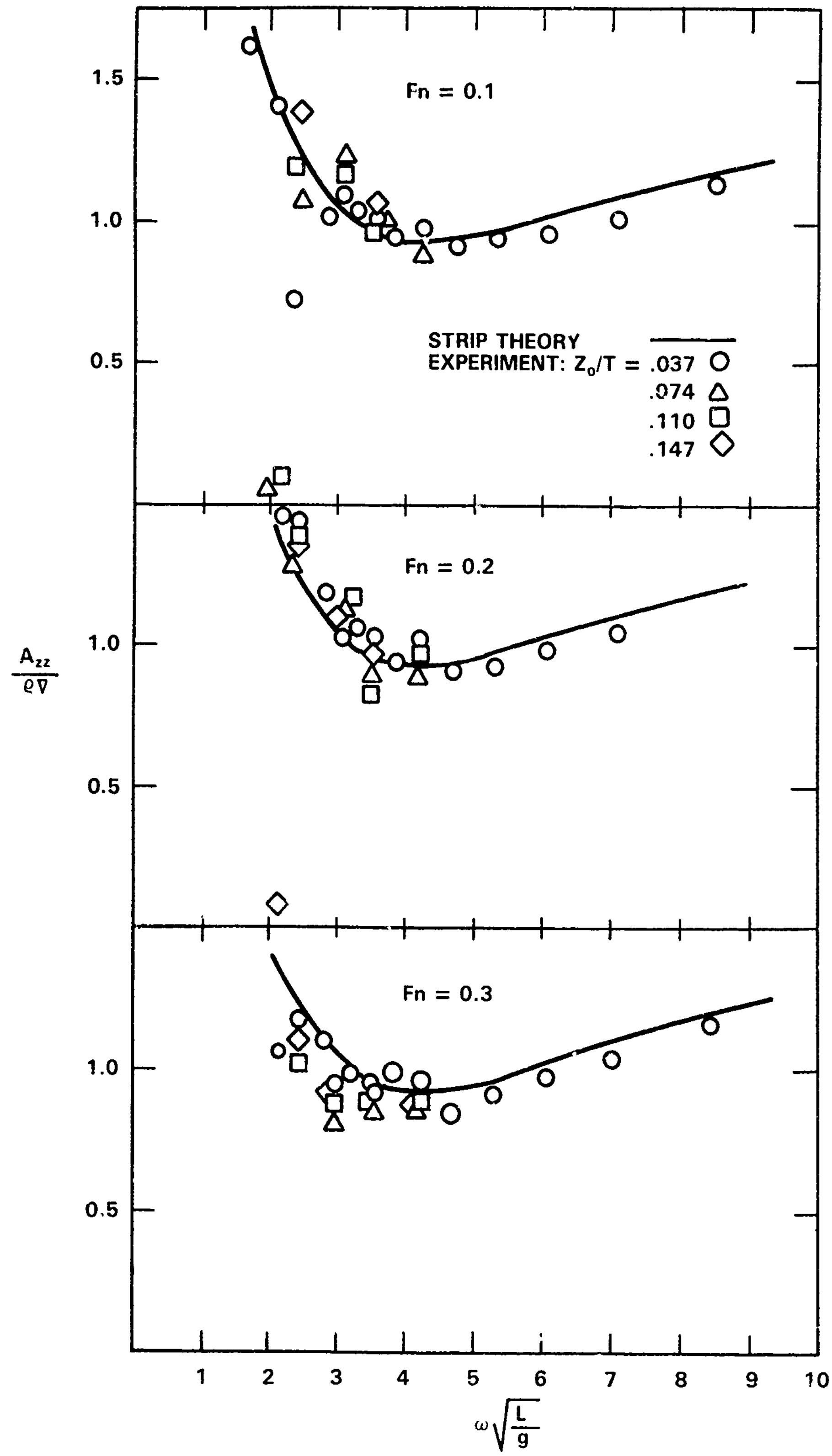

Figure 1 - Heave Added Mass Coefficient A_{zz}

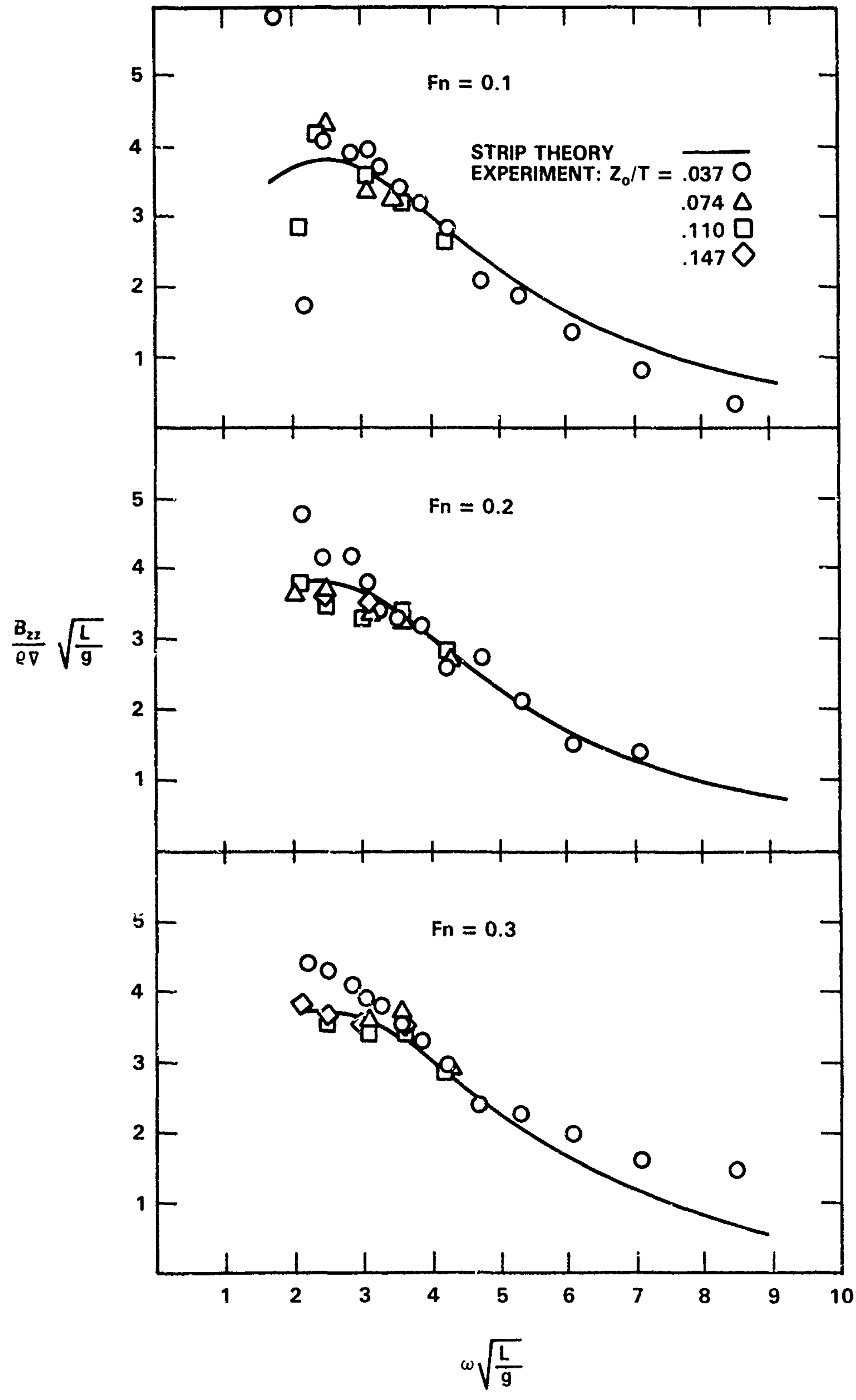

Figure 2 - Heave Damping Coefficient B_{zz}

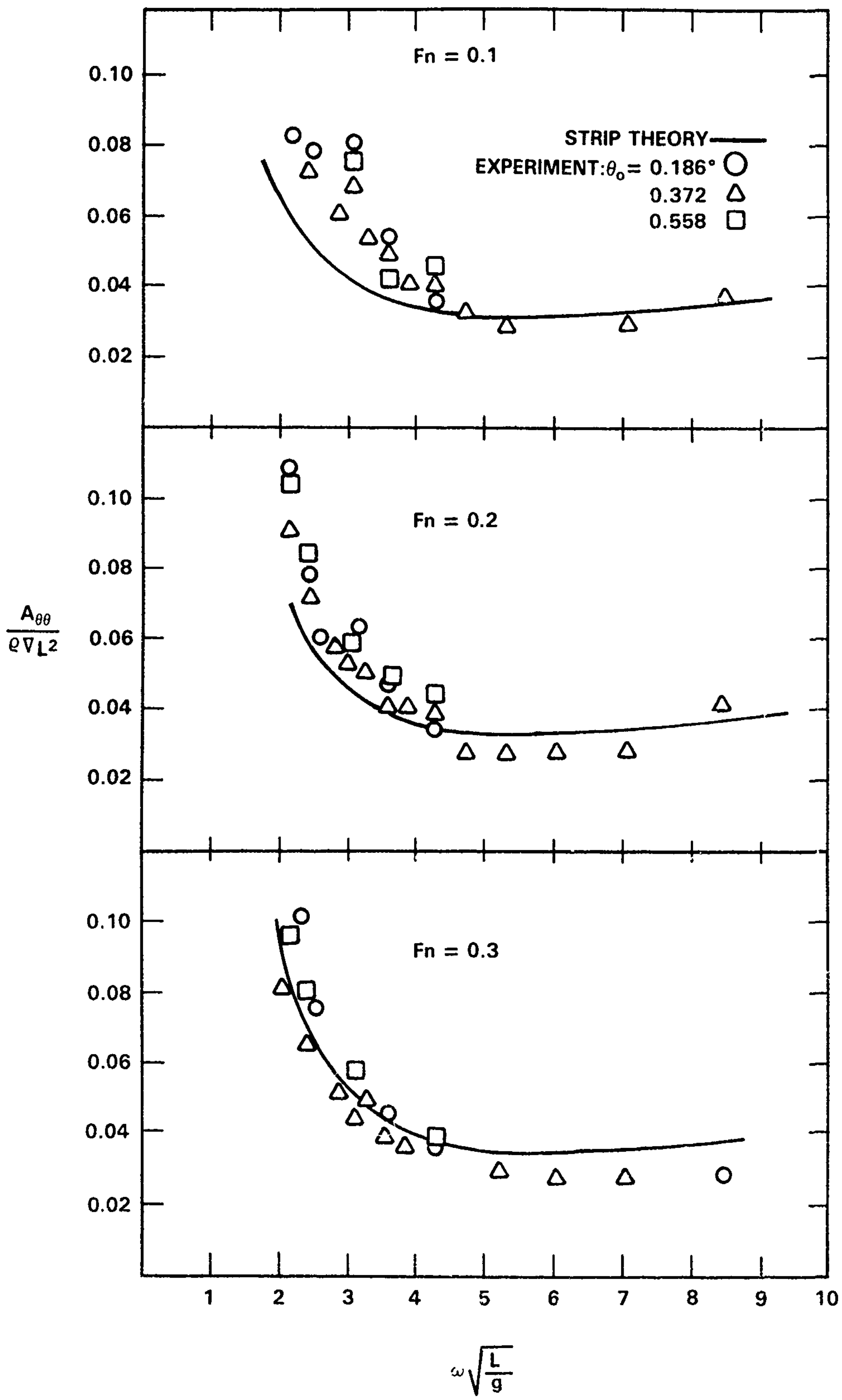

Figure 3 - Pitch Added Mass Coefficient $A_{\theta\theta}$

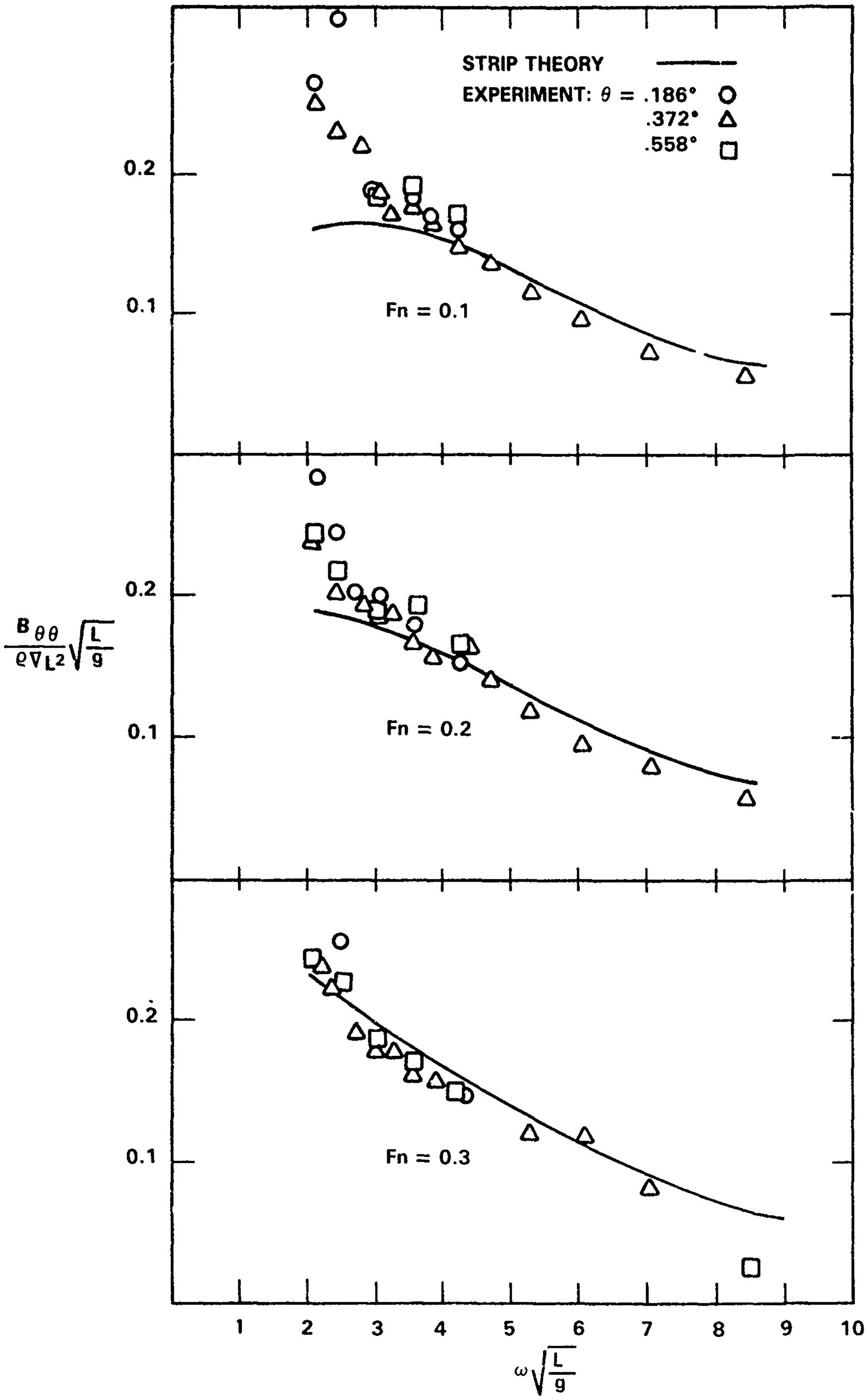

Figure 4 - Pitch Damping Coefficient $B_{\theta\theta}$

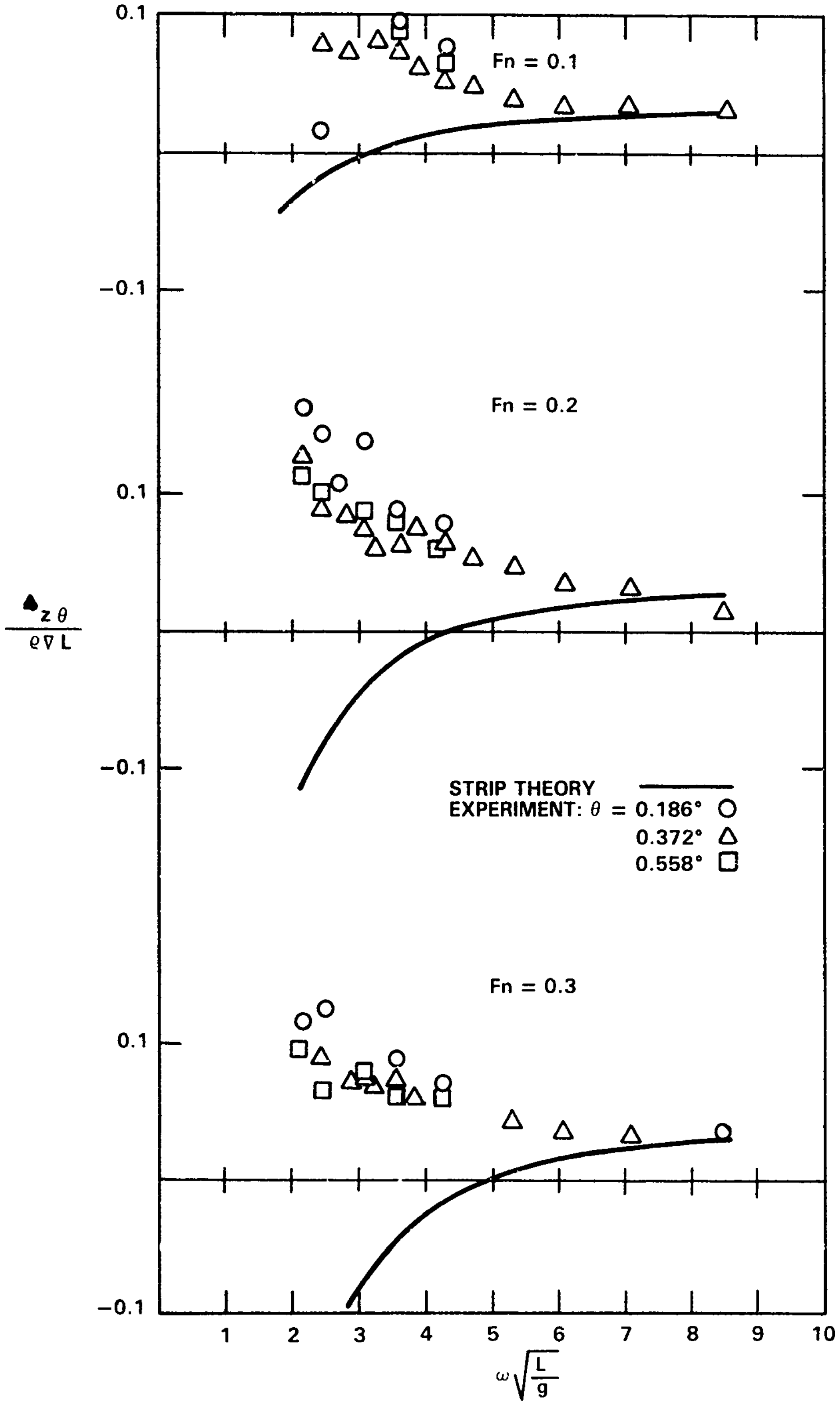

Figure 5 - Heave-Pitch Coupling Coefficient $A_{z\theta}$

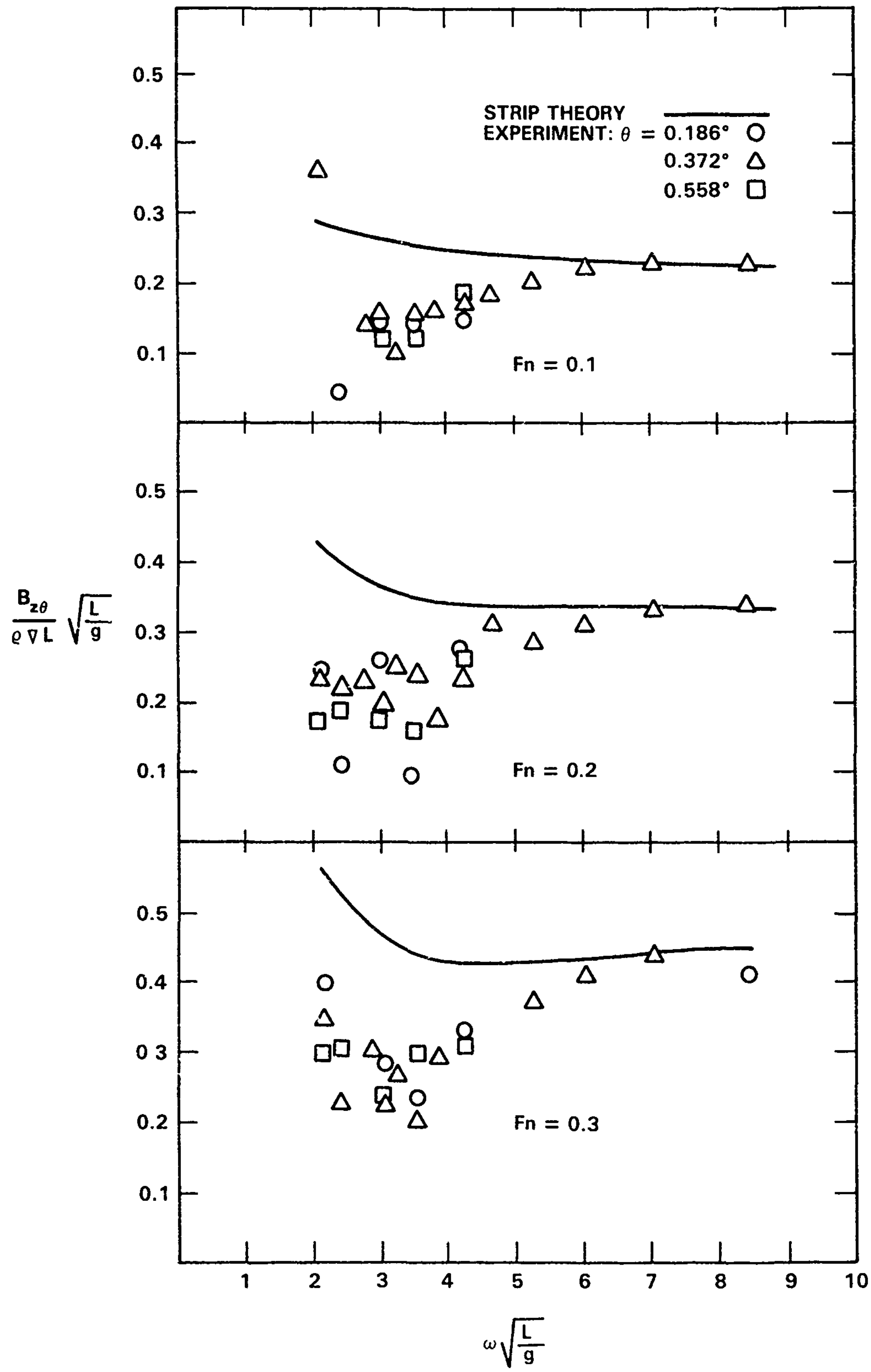

Figure 6 - Heave-Pitch Coupling Coefficient $B_{z\theta}$

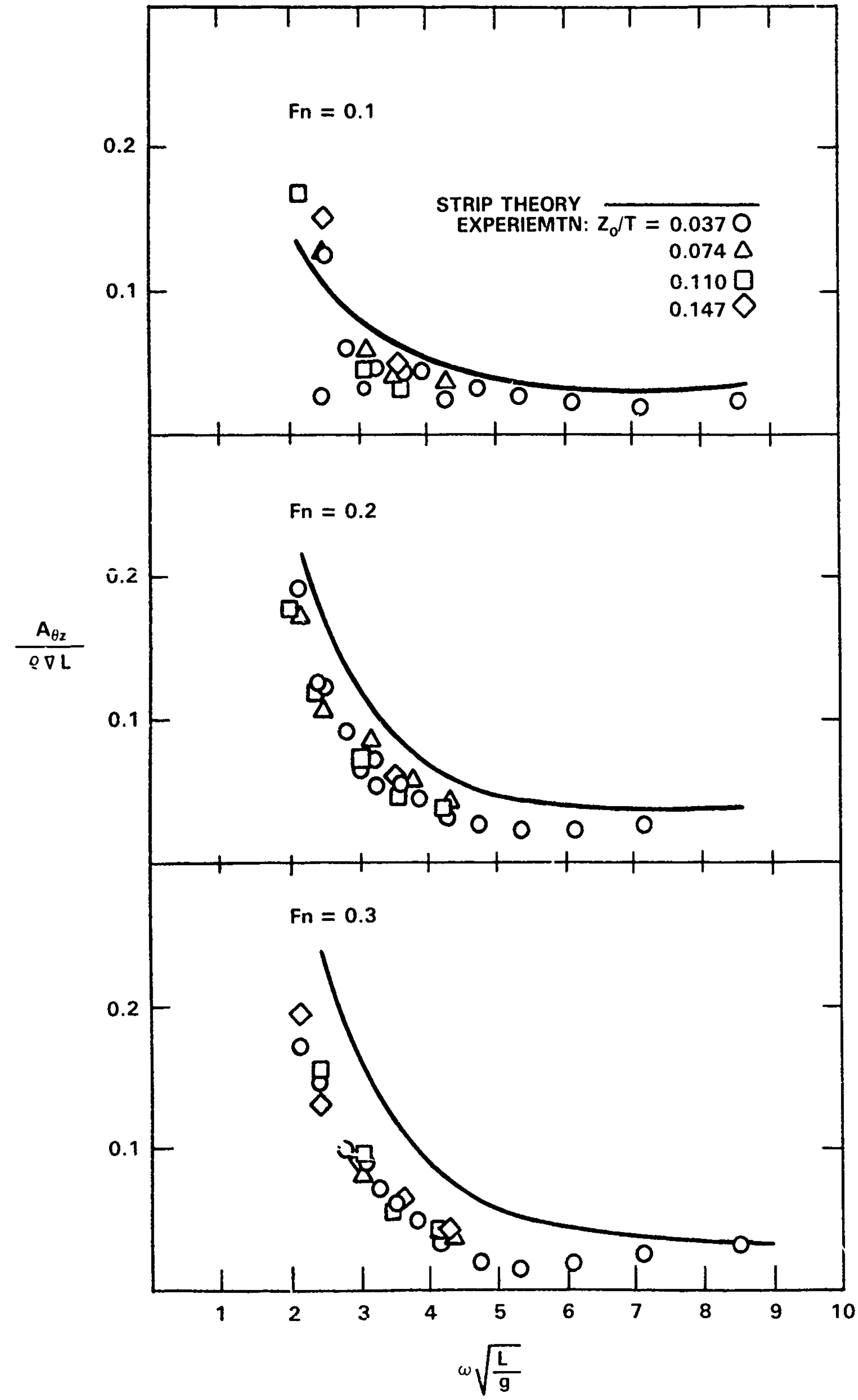

Figure 7 - Pitch-Heave Coupling Coefficient $A_{\theta Z}$

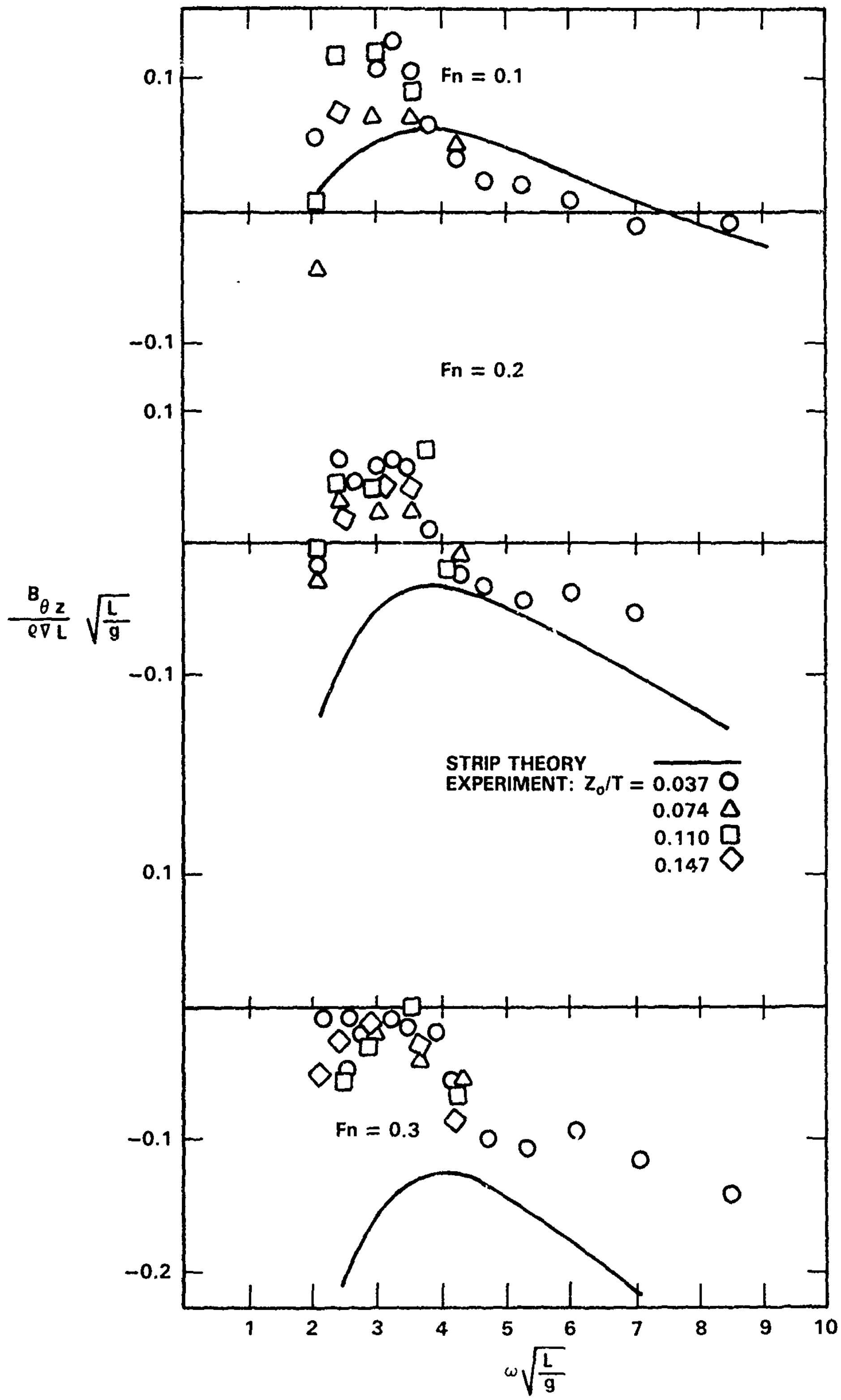

Figure 8 - Pitch-Heave Coupling Coefficient $B_{\theta z}$

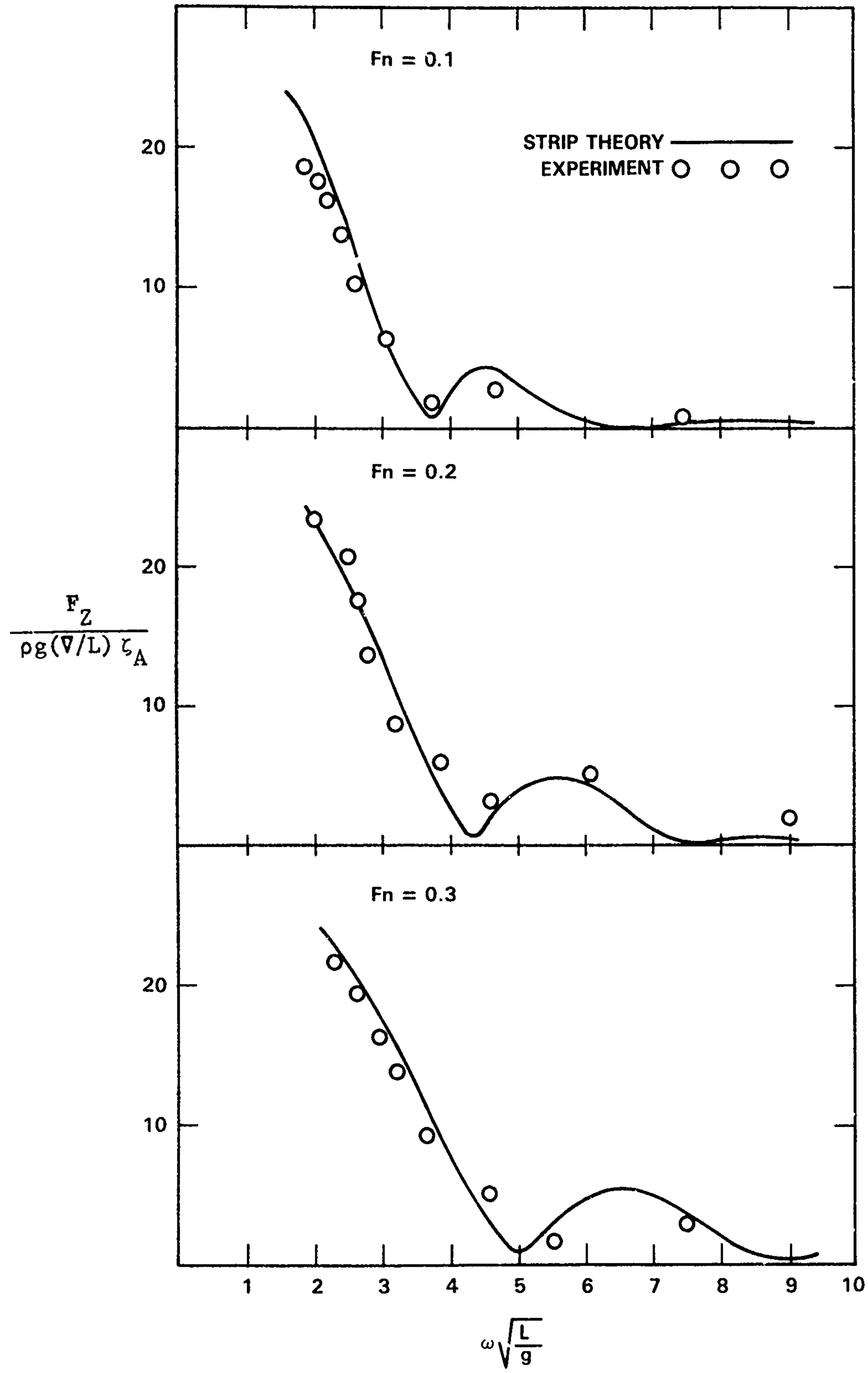

Figure 9 - Amplitude of Heave Exciting Force

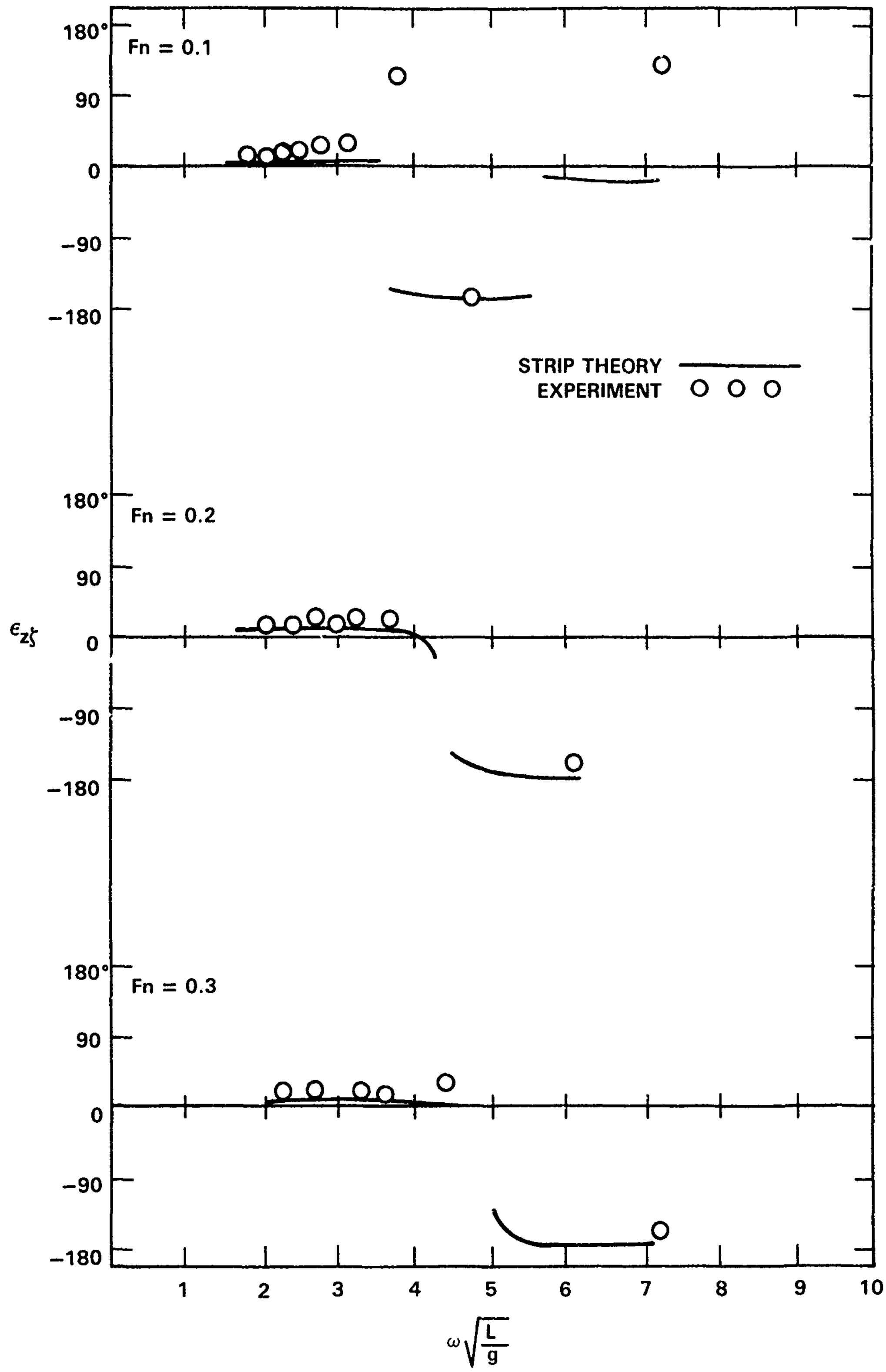

Figure 10 - Phase of Heave Exciting Force

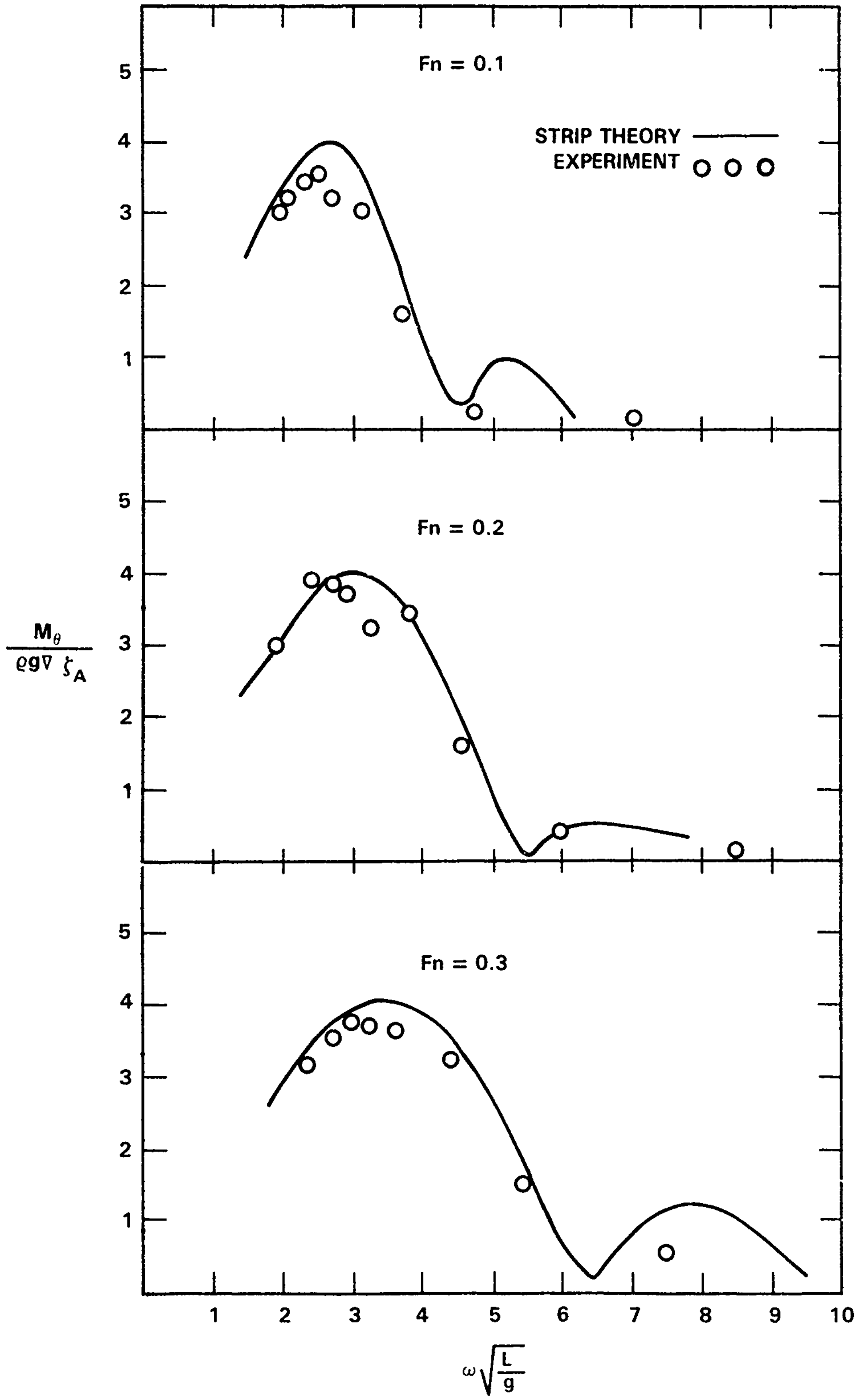

Figure 11 - Amplitude of Pitch Exciting Moment

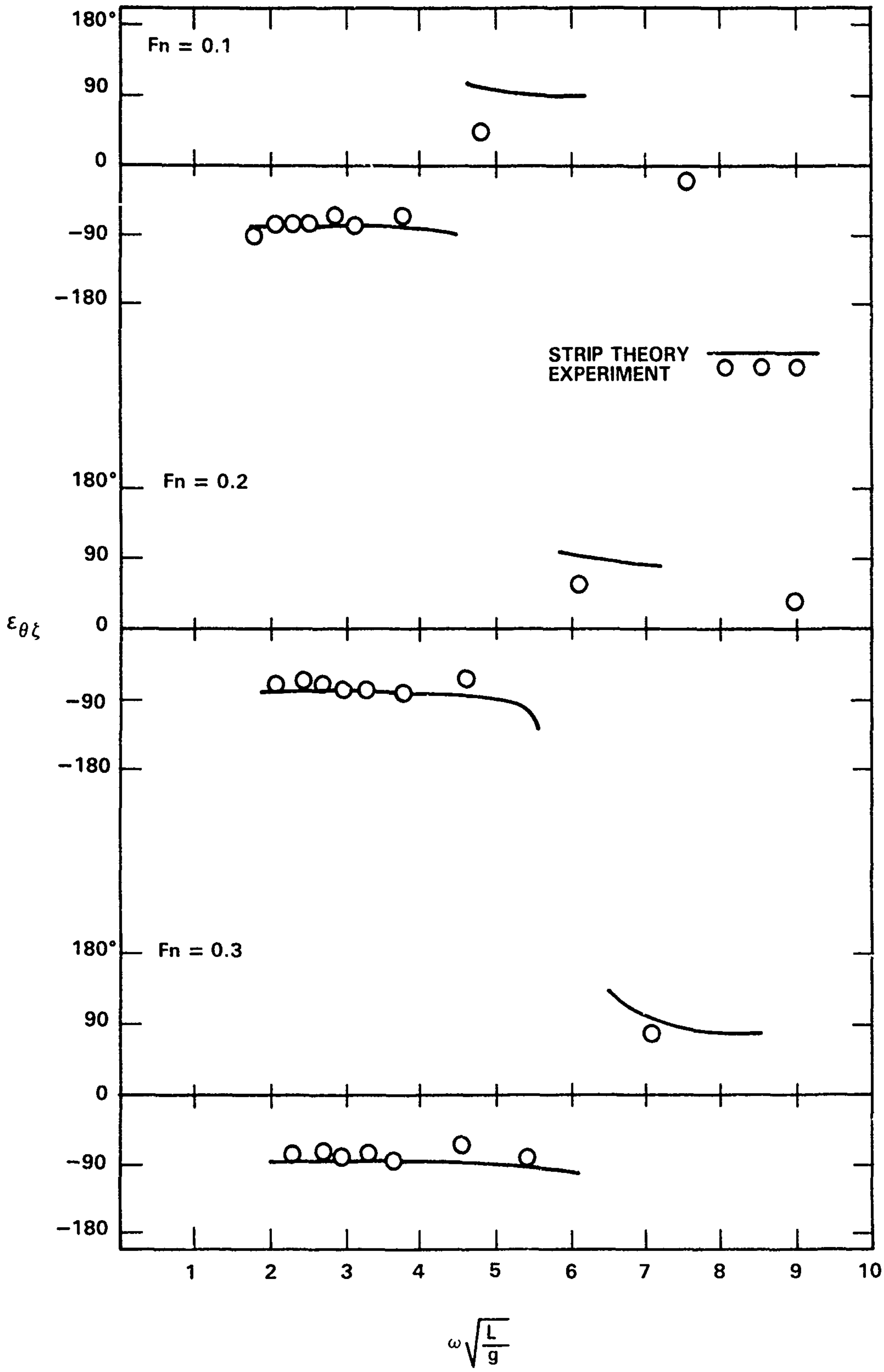

Figure 12 - Phase of Pitch Exciting Moment

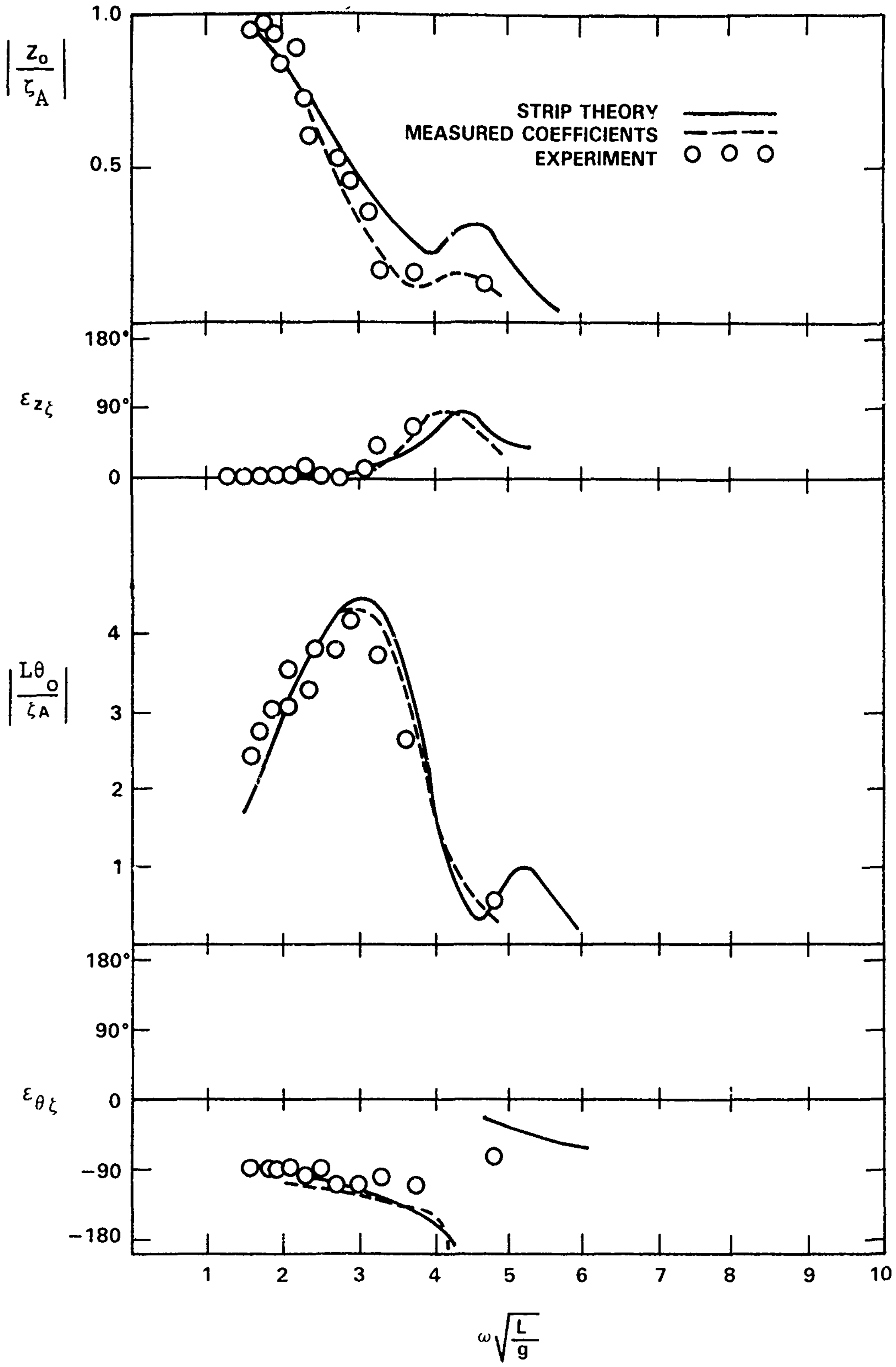

Figure 13 - Heave and Pitch Transfer Functions, Froude Number = 0.1

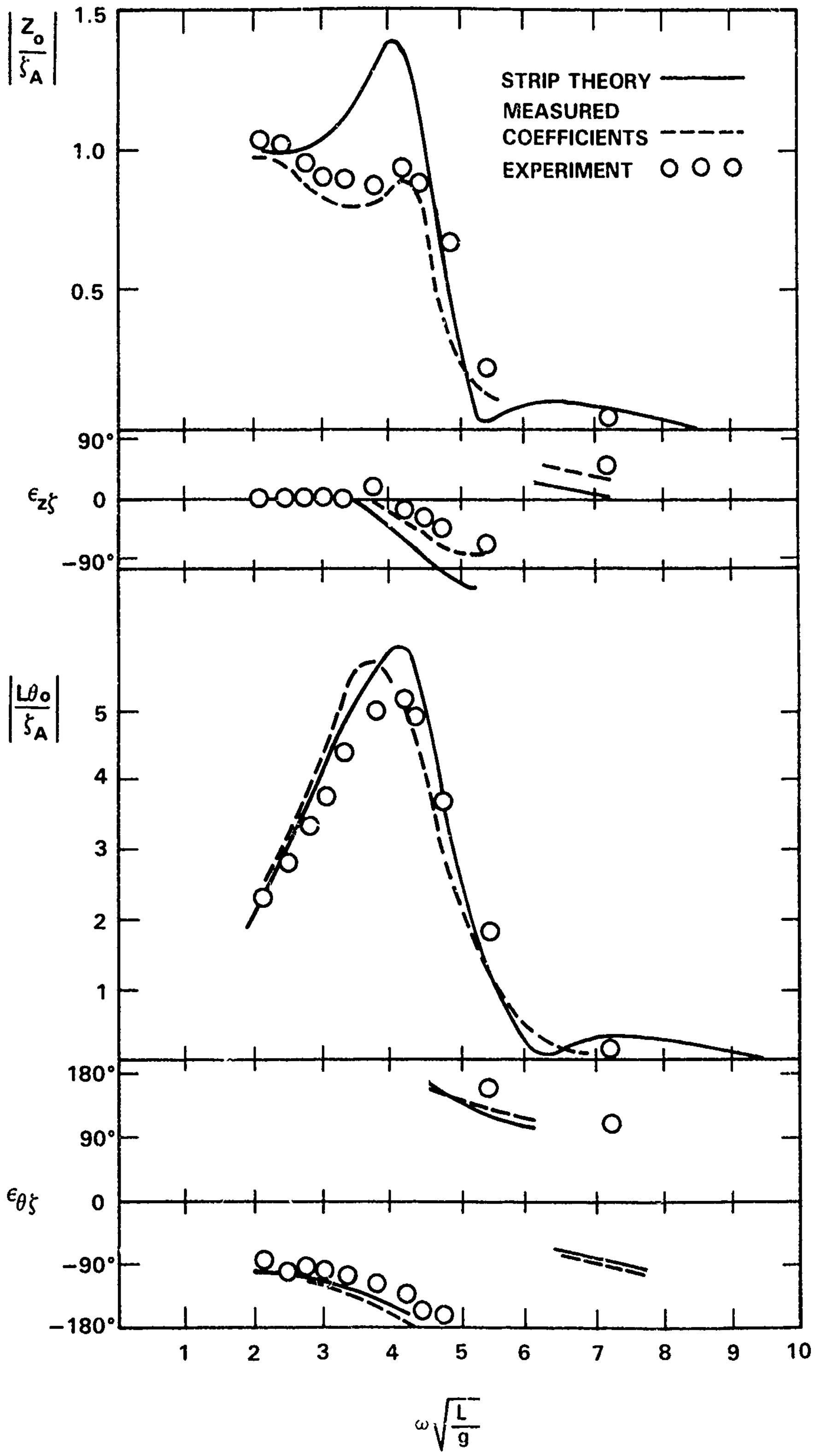

Figure 14 - Heave and Pitch Transfer Functions, Froude Number = 0.3

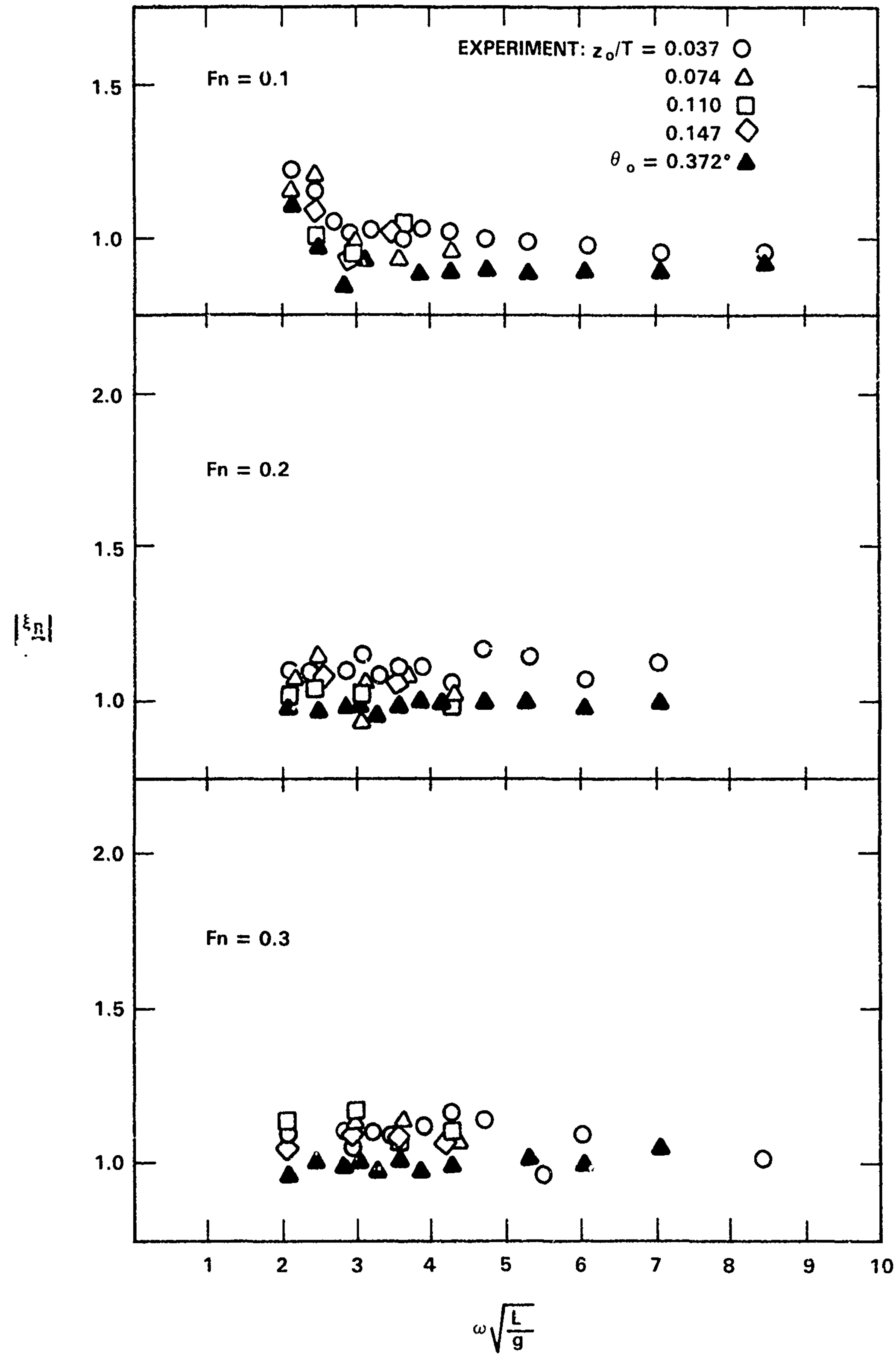

Figure 15 - Relative Motion at Station 0

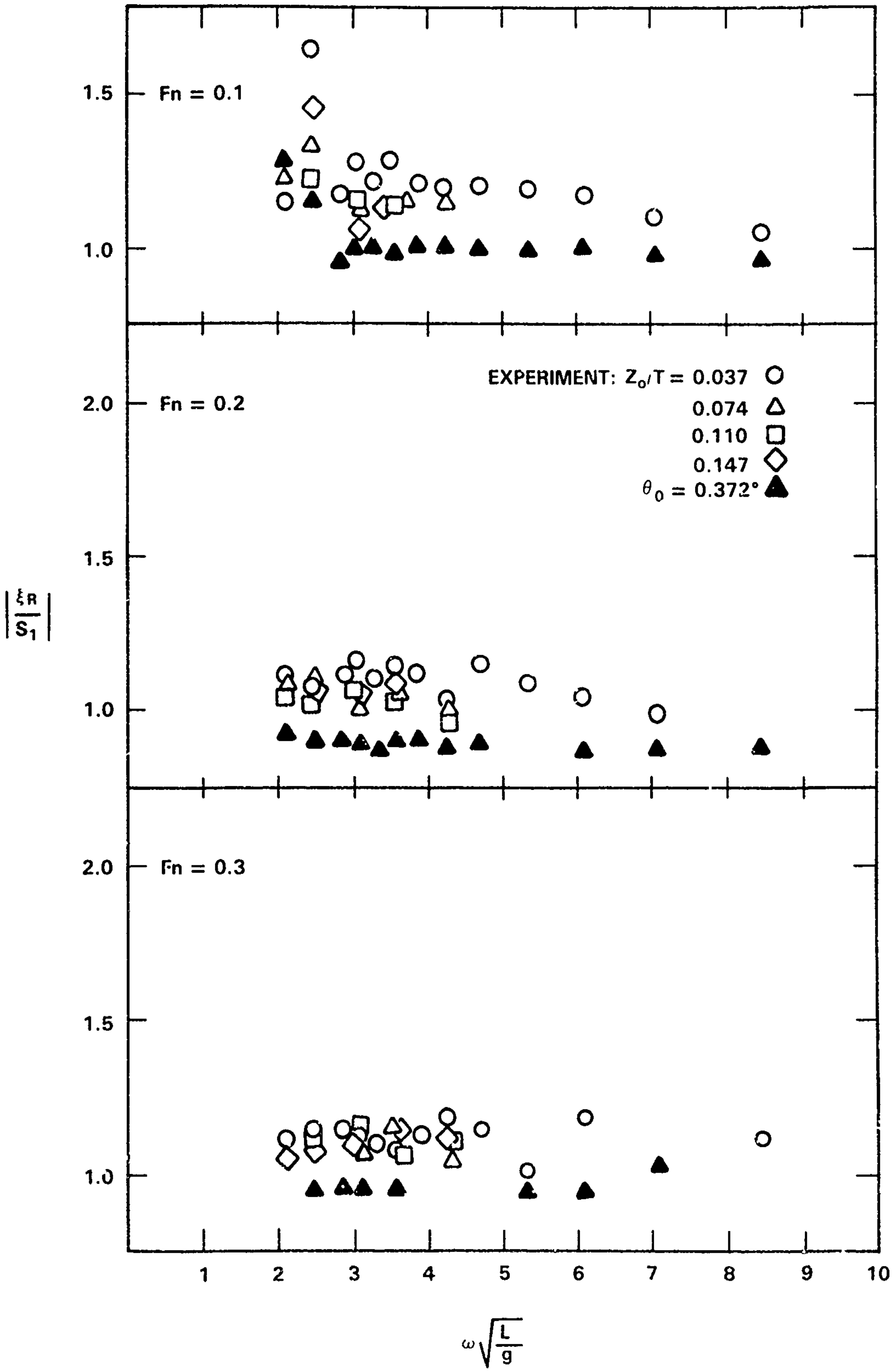

Figure 16 - Relative Motion at Station 1

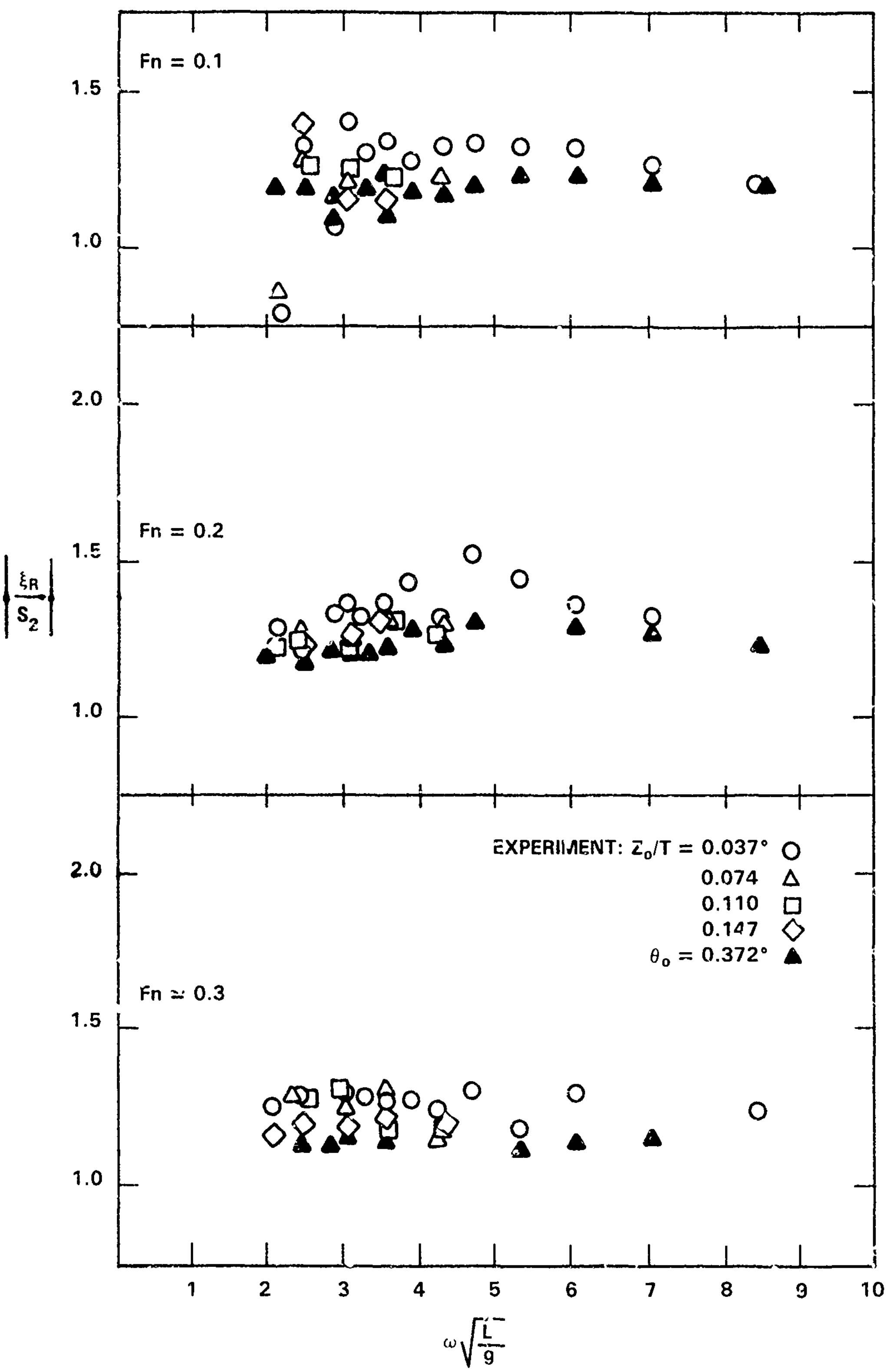

Figure 17 - Relative Motion at Station 2

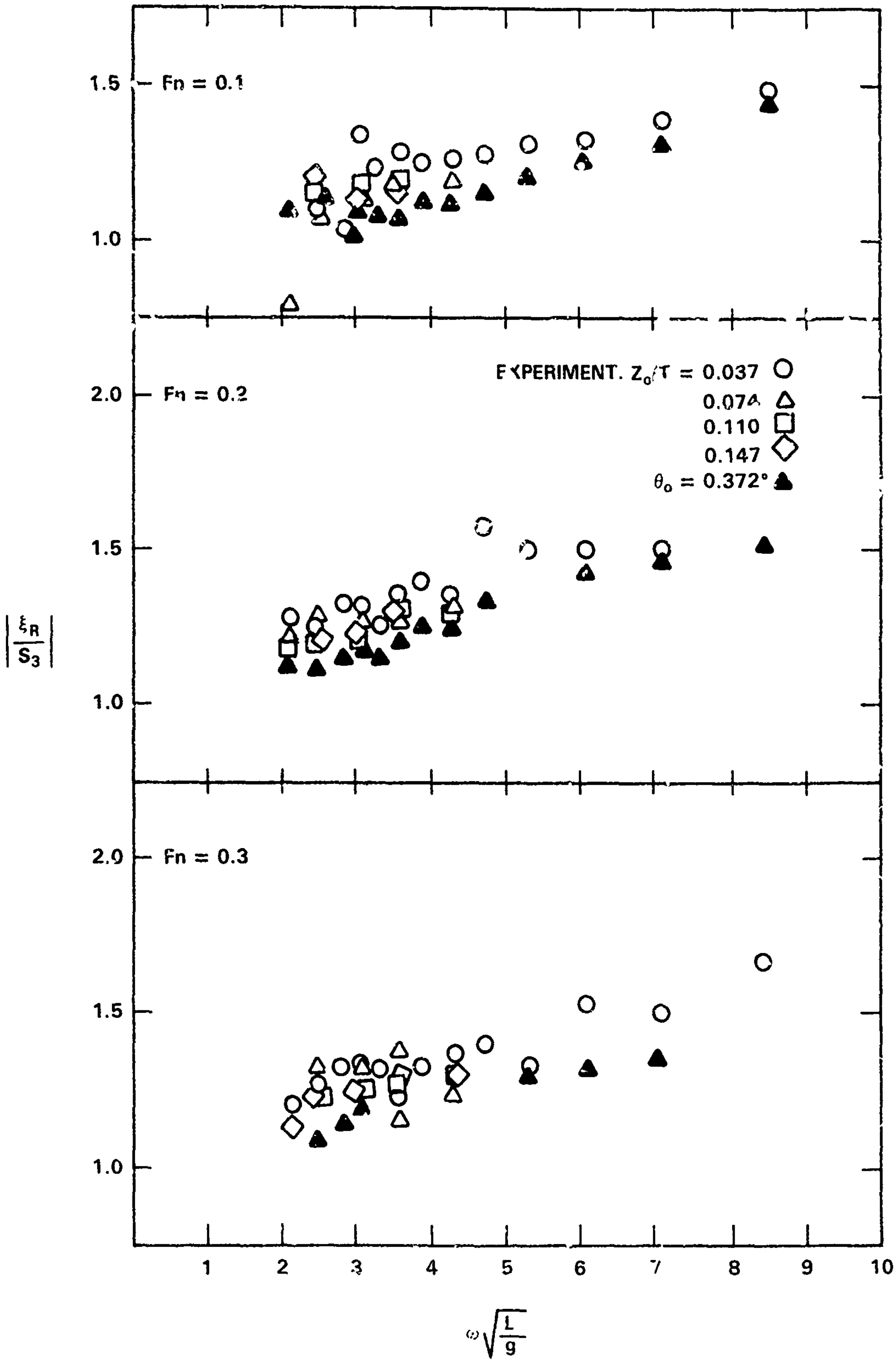

Figure 18 - Relative Motion at Station 3

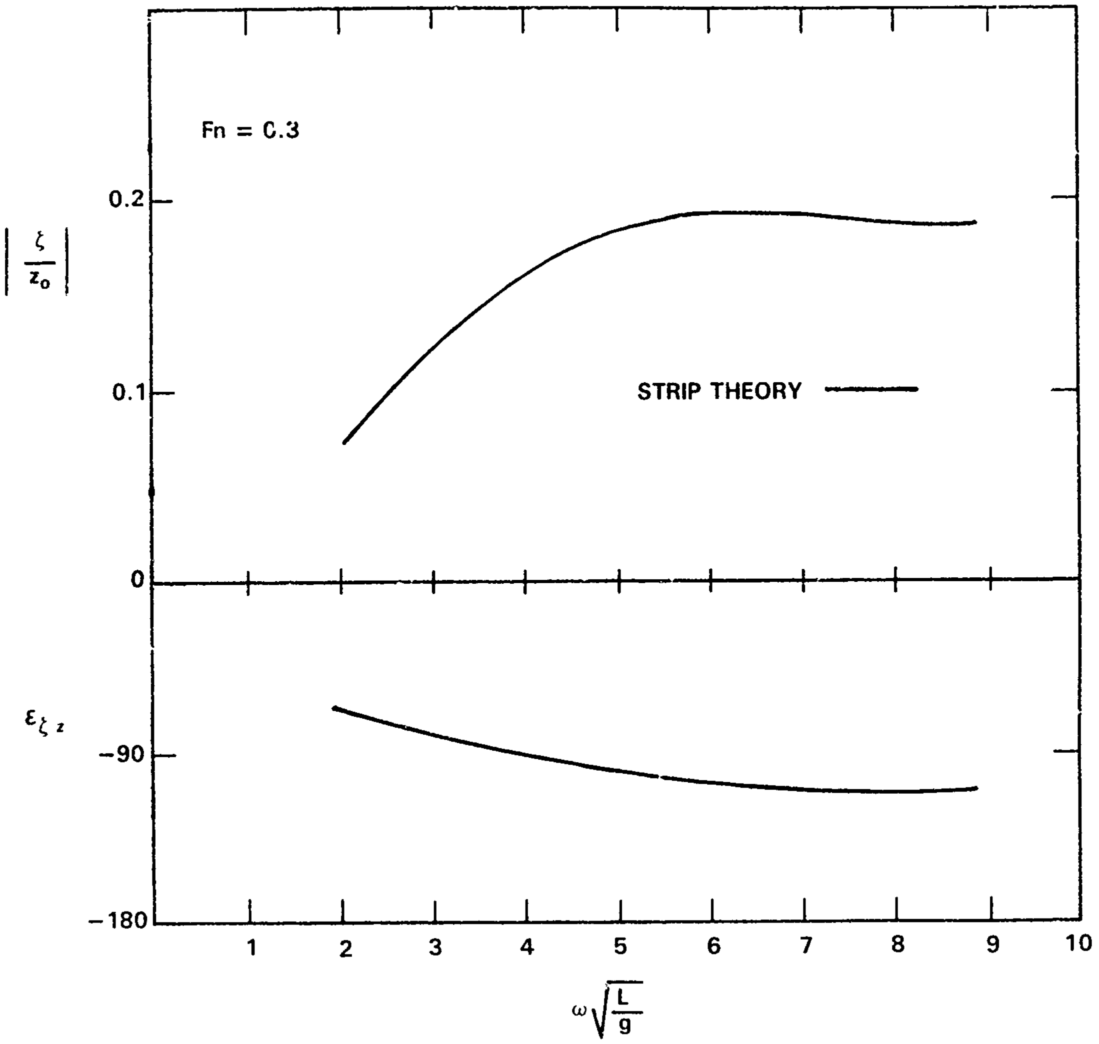

Figure 19 - Wave Component Caused by Heave Oscillation at Station 2

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